Environmental Pollution 243 (2018) 1008–1014

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

Biomass burning and carbon monoxide patterns in Brazil during the extreme drought years of 2005, 2010, and 2015☆

I.O. Ribeiro [a, *], R.V. Andreoli [b], M.T. Kayano [c], T.R. Sousa [d], A.S. Medeiros [a, e], R.H.M. Godoi [f], A.F.L. Godoi [f], S. Duvoisin Junior [b], S.T. Martin [g], R.A.F. Souza [b]

[a] Postgraduate Program in Climate and Environment (CLIAMB, INPA/UEA), Av. André Araújo, 2936, Campus II, Aleixo, 69060-001, Manaus, Amazonas, Brazil
[b] Amazonas State University, Superior School of Technology, Av. Darcy Vargas, 1200, Parque 10 de Novembro, 69065-020, Manaus, Amazonas, Brazil
[c] National Institute for Space Research, Center for Weather Forecasting and Climate Research, Av. dos Astronautas, 1758 São José dos Campos, 12227-010, São Paulo, Brazil
[d] Postgraduate Program in Ecology (PPG-ECO, INPA), Av. André Araújo, 97, Campus III, Adrianópolis, 69060-000, Manaus, Amazonas, Brazil
[e] Amazonas State University, Center of Superior Studies of Tefé, R. Brasília, 2127, Jerusalém, 69470-000, Tefé, Amazonas, Brazil
[f] Federal University of Parana, Environmental Engineering Department, Rua Francisco H. dos Santos, 100, Jardim das Américas, 81531-990, Curitiba, Paraná, Brazil
[g] School of Engineering and Applied Sciences, Harvard University 02138, Cambridge, MA, USA

ARTICLE INFO

Article history:
Received 5 April 2018
Received in revised form
22 August 2018
Accepted 4 September 2018
Available online 12 September 2018

Keywords:
Greenhouse gas
El Niño
Extreme events
Climate variability
Amazon

ABSTRACT

In the 21st century, severe droughts associated with climate change will increase biomass burning (BB) in Brazil caused by the human activities. Recent droughts, especially in 2005, 2010, and 2015, caused strong socioeconomic and environmental impacts. The 2015 drought considered the most severe since 1901, surpassed the 2005 and 2010 events in respect to area and duration. Herein, based on satellite data, the 2005, 2010 and 2015 drought impacts on wildfire episodes and carbon monoxide (CO) variability during the dry and the dry-to-wet transition seasons were examined. The BB occurrences in the dry season were fewer during 2015 than during 2005 (−44%) and 2010 (−47%). Contrasting, the BB events in the dry-to-wet transition season, were higher during 2015 than during 2005 (+192%) and 2010 (+332%). The BB outbreaks were concentrated in the southern and southwestern Amazon during 2005, in the Cerrado region during 2010, and mainly in the central and northern Amazon during 2015, an area normally with few fires. The CO concentration showed positive variations (up to +30%) occurred in the southern Amazon and central Brazil during the 2005 and 2010 dry seasons, and north of 20 °S during the 2015 −2016 dry-to-wet transition season. The BB outbreaks and the CO emissions showed a considerable spatiotemporal variability among the droughts of 2005, 2010, and 2016, first of them driven by local conditions in the tropical North Atlantic (TNA), characterized by warm than normal sea surface waters and the other two by the El Niño occurrences.

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1. Introduction

Under climate change the long-range simulations with global and regional climate model put in perspective the future scenario in large Brazilian areas with more frequent and intense droughts, which are expected to increase the risk of the forest fires (Salazar et al., 2007). After the 1990s, several severe droughts (1995, 1997, 1998, 2005, 2010, 2012, and recently 2015) occurred in distinct Brazilian areas. Concomitantly, the expansion of livestock activities towards the central and northern regions of Brazil, motivated by the economic policy on the ample use of the natural resources, cause an intensification of the land use with consequence alterations in the land cover in these regions. In general, these activities were linked to the fire use for cleaning pastures. This lead to high deforestation rates in Brazil, where the frequency of the forest fires and their severity were amplified in dry years (Fernandes et al., 2011; Van Der Werf et al., 2017; Aragão et al., 2018; Ribeiro et al., 2018).

Forest fires increase the carbon and aerosol emission into the atmosphere, affecting locally and globally the environmental systems (e.g. hydrologic cycle behavior, radiation balance, air quality)

☆ This paper has been recommended for acceptance by Charles Wong.

* Corresponding author.
E-mail address: ior.dcl@uea.edu.br (I.O. Ribeiro).

https://doi.org/10.1016/j.envpol.2018.09.022
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(Aragão et al., 2007; Van Der Werf et al., 2010; Artaxo et al., 2013; Saito et al., 2016). Chemically reactive gases like carbon monoxide (CO) comes mainly from the biomass burning (BB), especially in Brazil, a tropical region. This gas is the second most crucial compound emitted in the BB, behind only of the CO_2, and represents about 2–10% mass of fuel carbon (Lobert and Warnatz, 1993). Santos et al. (2017) found maximum CO emission values in the South American band between 5° S and 20° S, which were associated with BB in the Amazon and Cerrado forests, mainly during the dry season of the 2005 and 2010 dry years.

In recent decades, tropical Brazil, particularly the Amazon, experienced extreme droughts, which were modulated by the anomalous sea surface temperature conditions in the tropical Pacific and tropical North Atlantic (TNA) featuring, an El Niño and warming, respectively. For conciseness, hereinafter the anomalously warm condition in the TNA is referred to as the TNA warming. The Amazon extreme droughts, one in 2005 and another in 2010 were considered as the most severe ones for the last 100 years (Marengo et al., 2011). The 2005 drought extended over southwestern Amazon and northern of Northeastern Brazil (NEB) and driven by the TNA warming (Aragão et al., 2007; Marengo et al., 2008; Erfanian et al., 2017). The Amazon precipitation reduced (augmented) in its southwestern (northeastern) sector during the dry (wet) season, and the dryness extended over an approximated area of 1.9×10^6 km^2 being more severe in July-August-September (JAS) (Lewis et al., 2011; Erfanian et al., 2017). During 2005, the amount of BB outbreaks in the Amazon, mainly in its southern sector ("deforestation arc") was 33% above the mean of the 1999–2005 period (Aragão et al., 2007). These BB outbreaks had a significant contribution carbon emission in South America which was estimated as of 472 Tg C yr^{-1} (Van Der Werf et al., 2010).

The 2010 drought was triggered during early austral summer by an El Niño and became intensified due to the subsequent TNA warming (Marengo et al., 2011; Coelho et al., 2012; Marengo and Espinoza, 2016; Panisset et al., 2018). In extended over the Amazon Basin and NEB and was more severe than that of 2005. The precipitation reduction in the Amazon during the dry season covered over 3.0×10^6 km^2 (Lewis et al., 2011). The precipitation deficit in NEB occurred in its northern sector from September to November, and in its southern sector, from June to July (Erfanian et al., 2017). In the 2010 year, the BB outbreaks in the Amazon and central Brazil regions has substantial contributions to the carbon emission in South America which was approximately of 600 Tg C yr^{-1} (Van Der Werf et al., 2010).

An unprecedented drought affecting mainly the Amazon and NEB was registered during the 2015–2016 period. This event, considered the most severe since 1901, exceeded the previous ones in severity and extension, affecting more than 80% of the Amazon Basin. It spanned from September 2015 to May 2016. Aragão et al. (2018) analyzed the effects of droughts on the forest fire incidence and the related carbon emission in the Amazon over the 2003–2015 period. They found an increase of 36% in the forest fire incidence during 2015 in relation to the average of the 2003–2014 period. In addition, Aragão et al. (2018) showed that C emissions from the Amazon due to burning in the areas with secondary vegetation and pasture were greater than those directly associated with burning of primary vegetation during 2015. Several factors contributed to the occurrence of this extreme drought event: the El Niño and TNA warming were the main drivers (Erfanian et al., 2017; Panisset et al., 2018). Erfanian et al. (2017) argued that these oceanic conditions did not explain the exceptional severity of the drought, and suggested that others factors such as land use and CO_2 warming contributed to the intense drought. Jiménez-Muñoz et al. (2016) suggested that the strong El Niño, combined with a regional warming trend of the land surface temperature, was associated with the drought. They argued that the central Pacific El Niño or Modoki El Niño type (Ashok et al., 2007) caused an anomalous precipitation dipole structure between southwestern (wet) and northeastern (dry) Amazon.

Different from the Cerrado region, natural forest fires in the Amazon were rare due to the tropical features of the biome (i.e., high humidity and moisture content) and low frequency of extreme drought events. Because of the rarity, the native vegetation in the Amazon forest did not develop resilience to fire, increasing its vulnerability during severe drought events associated with fire increases (Hardesty et al., 2005; Pivello, 2011).

The future scenario in the Amazon includes alterations in the hydrological regime, increases in the air temperature, drought severity and amount of the forest fires, and changes in the biome (Aragão et al., 2007; Malhi et al., 2008; Erfanian et al., 2017; Panisset et al., 2018). Therefore, the Amazon role as carbon sink to the atmosphere would be altered (Phillips et al., 2009) and the global warming would be favored (Scott et al., 2018), leading to positive climate-vegetation feedback process in the Amazon (Marengo and Espinoza, 2016).

Considering all these aspects, a better understanding of the effects of forest fires as an environmental question is required (Van Der Werf et al., 2010; van Marle et al., 2017; Ribeiro et al., 2018). In the present analysis, we focus further on relationships of the 2005, 2010 and 2015 droughts and the BB outbreaks and CO variability over Brazil, using satellite observations.

1.1. Data and methodology

Daily BB outbreak data, available at 3 h intervals, obtained from the Brazilian National Institute for Space Research (INPE) (https://prodwww-queimadas.dgi.inpe.br/bdqueimadas) for the 2003–2016 period, were used. Between 1999 and 2007, these data were based on estimates from the NOAA-12 satellite and from 2008 on the AQUA satellite.

The CO data were from the National Aeronautics and Space Administration (NASA) Goddard Earth Sciences Data and Information Services Center (DISC) and were estimated from the Atmospheric Infrared Sounder (AIRS) sensor on board the AQUA satellite and available. Only the CO data with the quality control index 0 and 1 of the AIRS Level 3 Standard Gridded Version 6 product (L3-AIRX3ST8), were used. The CO data are in a horizontal grid 1° by 1°. Additional information can be at http://docserver.gesdisc.eosdis.nasa.gov/repository/Mission/AIRS/3.3_ScienceDataProductDocumentation/3.3.4_ProductGenerationAlgorithms/V6_L3_User_Guide.pdf. The data consist of eight-day average of the vertically integrated CO content for the 2003 to 2016 period (635 data-sets in time) (AIRS Science Team/Joao Texeira, 2013).

The monthly CMAP (CPC Merged Analysis of Precipitation) precipitation data for the 2003–2016 period were used here. These data are based on raingauge observations, satellite estimates and numerical model outputs and are in a horizontal grid with 2.5° by 2.5° resolution. The CMAP Precipitation data were provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their web site at https://www.esrl.noaa.gov/psd/. Additional information can be at https://climatedataguide.ucar.edu/climate-data/cmap-cpc-merged-analysis-precipitation.

Analyses were done for the period from July to March of the 2005/06, 2010/11 and 2015/16 years, when the dryness in the Amazon Basin and NEB was most severe (Marengo et al., 2008, 2011; Jiménez-Muñoz et al., 2016; Erfanian et al., 2017; Panisset et al., 2018). Regarding to the Amazon, this period spans over its dry season (July to October - JASO) and it dry-to-wet transition season (November to March - NDJFM).

The number of BB events over Brazil was accumulated for each

month of the 2005, 2010, and 2015 droughts. The monthly percentage variations of the number of the BB during 2015 relative to the other two drought years were calculated. The variation (%) of a given value V_1 in relation to a reference value V_r is given by:

$$Variation\ (\%) = \left[\frac{(V_1 - V_r)}{V_r}\right] x\ 100$$

The monthly patterns of the BB occurrences over Brazil were estimated by the Kernel technique for the 2003–2016 period. This technique was described in Ribeiro et al. (2018). The seasonal (JASO and NDJFM) standardized anomaly maps of the BB outbreaks and average accumulated precipitation for the 2005, 2010 and 2015 were obtained taking into account the means and standard deviations (σ) over the 2003–2016 period.

The same analysis procedures used by Ribeiro et al. (2018) were adopted here. So, firstly monthly CO values (average of eight-day values of each month) were obtained for each year. Then, monthly mean values were calculated. The CO eight-day anomalies were obtained by subtracting from the eight-day values the corresponding month average value. Standardized monthly anomalies were also obtained. The seasonal (JASO and NDJFM) CO variations of the 2005, 2010 and 2015 in relation to the seasonal averages of the 2003–2016 period were also analyzed. For a given grid point, the seasonal value was obtained for each year by averaging all eight-day CO value that entered in that season and year. Then, the season average was obtained considering the 2003–2016 period. This seasonal average is the reference value (V_r) that enters in the variation calculation.

2. Results and discussions

Monthly accumulated numbers of the BB events over Brazil during the 2005, 2010, and 2015 are shown in Fig. 1. For all three droughts, the highest numbers of the BB outbreaks occurred from August to October, a period that overlaps the Amazon dry season (Fig. 1). A peak in September with over than 80,000 fire outbreaks occurred during 2010. The numbers of the BB outbreaks during the 2005 and 2010 dry seasons exceeded, respectively, by 44% and 47% those of the 2015 dry season. The accumulated numbers of the BB events during 2015 also peaked during the dry season, but those during the dry-to-wet transition season (November to March) surpassed the corresponding ones of the other years (2005, 2010). On the other hand, the accumulated numbers of the BB events during the dry-to-wet transition season of the 2015–2016 period surpassed the corresponding ones for the other years (2005, 2010). In this case, the numbers of the BB events during the 2015 dry-to-wet transition season was increased by 192% and 332% relative to those of the 2005 and 2010 dry-to-wet transition seasons, respectively (Table 1), with the highest on record December to March dating back to 1998 (INPE, 2018).

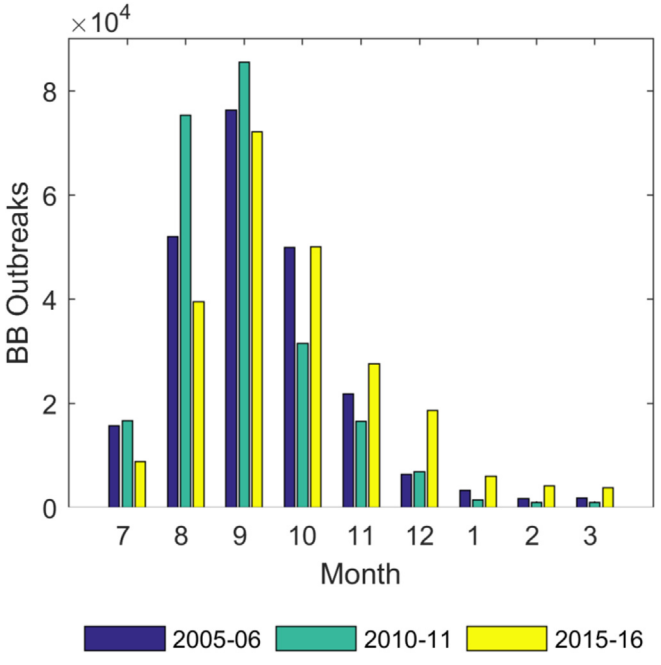

Fig. 1. Monthly number of the BB outbreaks in Brazil in 2005, 2010, and 2015. The numbers on the abscissa represent months.

The positive BB outbreak anomalies were found in the southwestern, southern and eastern Amazon Basin for the 2005 dry season (Fig. 2). These anomalies were closely linked to the anomalous dryness in these areas where the anomalies were less than -1σ (Fig. 3). The dryness in the southwestern, southern and eastern Amazon, was modulated by the TNA warming (Aragão et al., 2007; Marengo et al., 2008; Erfanian et al., 2017). The largest positive BB outbreak anomalies were noted in the "deforestation arc", a region known due to the land use for agricultural and livestock expansion. Our results confirm previous findings on the forest fire incidence in the southwestern Amazon, in particular in Acre, during the 2005 dry year (Aragão et al., 2007; Shimabukuro et al., 2009). According to Shimabukuro et al. (2009), a forested area of 2800 km^2 in Acre was burned due to a combination of a severe drought, deforestation, and land maintenance activities.

The frequency of the BB from November to March of 2005/06 increased in Central Brazil, a region of the Cerrado biome (Fig. 2). This occurred due to the deficient rainfall in this region, where rainfall anomalies less than -1σ were registered (Fig. 3). According to Marcuzzo et al. (2012), in January 2006, this region experienced precipitation scarcity, when precipitation was below 200 mm, the third lowest January value since 1977. In this region, the BB outbreaks were recurrent due to the local environmental features of high air temperature, long-lasting drought, and native flammable vegetation like grasses, bushes, and small palms trees. In the Cerrado, dry periods within the rainy season commonly occur. A few days without rain is sufficient to dry out the water accumulated in the soil and the biomass and to increase the risks of the BB outbreaks (Hardesty et al., 2005; Pivello, 2011; Durigan and Ratter, 2016).

In the case of the 2010 dry season, positive BB outbreak anomalies were noted in the northern and southern Amazon, in southern and northwestern NEB, and in the Cerrado. The latter was the most affected region where the number of the BB outbreaks exceeded 3σ (Fig. 2). In relation to the 2005 drought, that in 2010 was considered more severe and extensive and was controlled by the El Niño and TNA warming (Marengo et al., 2011). The areas with

Table 1
Variation (%) of the number of BB events of 2015 in relation to the 2005 and 2010.

Month	2005	2010
July 2015	−44.2	−47.5
August	−24.2	−47.6
September	−5.5	−15.7
October	+0.2	+58.7
November	+26.6	+66.1
December	+192.5	+171.3
January 2016	+83.4	+324.1
February	+148.6	+332.2
March	+113.1	+305.8

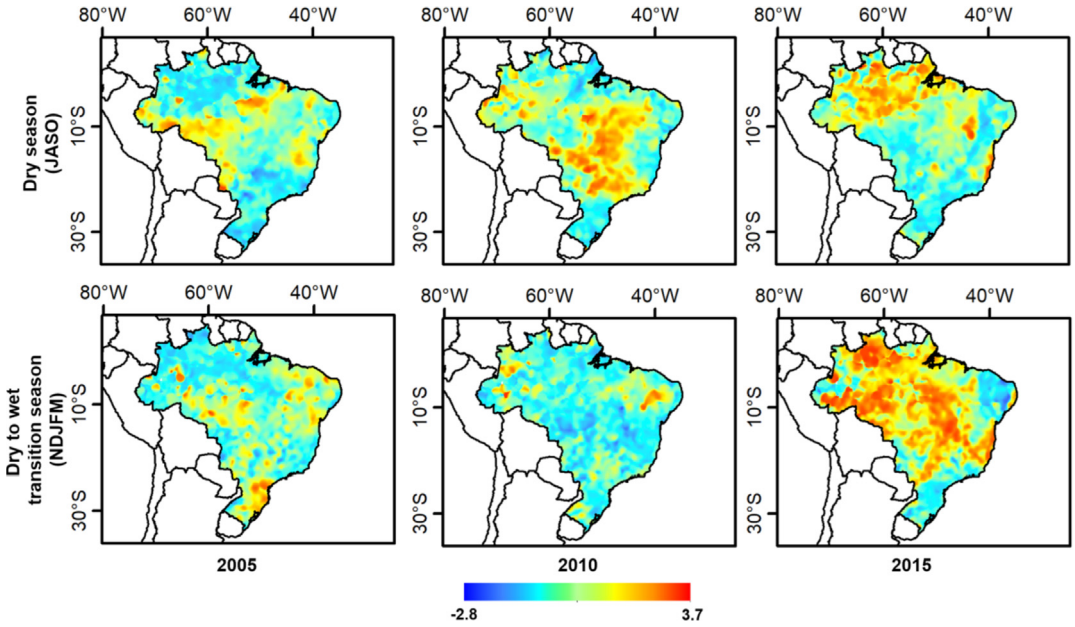

Fig. 2. Seasonal standardized anomalies of the BB outbreaks during the dry and dry-to-wet transition seasons of 2005, 2010 and 2015. The color bar varies from −2.8σ (blue) to 3.7σ (red).

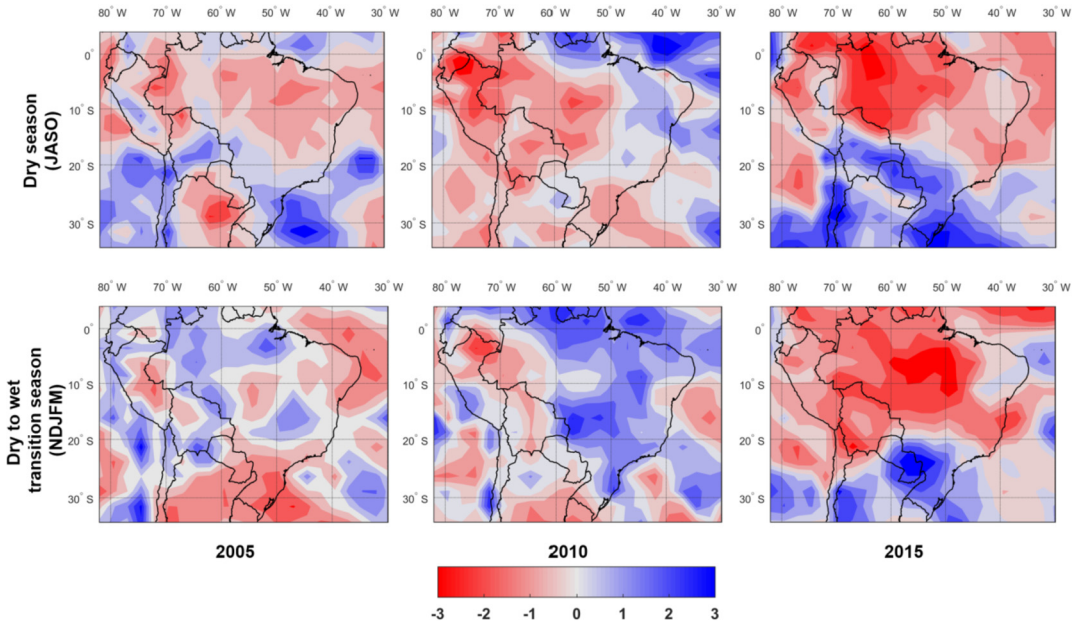

Fig. 3. Seasonal standardized anomalies of the average accumulated precipitation during the dry and dry-to-wet transition seasons of 2005, 2010 and 2015. The color bar varies from −3.0σ (red) to 3.0σ (blue).

positive BB outbreak anomalies during JASO 2010 (Fig. 2) coincide approximately with the noted 2010 drought areas, where occurred negative precipitation anomalies up to -3σ (Fig. 3). On the other hand, the widespread negative BB outbreak anomalies over Brazil, except for central NEB, from November to March, were associated with the previously documented anomalous wetness in this region caused by the El Niño event (Erfanian et al., 2017).

The 2015 drought was extraordinarily severe and affected over 80% of the Amazon basin (Fig. 3). High numbers of the BB events occurred in large areas of the Amazon from July to March (Fig. 2). In 2015, the areas affected by forest fires extended from the northern Amazon Basin into the eastern coast of Brazil with the highest number of the BB events in the central Amazon for the dry season, and in the northern Amazon Basin, Cerrado and the eastern coast of Brazil for the dry-to-wet season. In the case of the dry-to-wet transition season, the positive BB outbreak anomalies resulted from the BB events in northern Amazon in January 2016, in central and northern Brazil in February, and in central Brazil in March. Therefore, several Brazilian states (including Mato Grosso, Amazonas, Pará, Espírito Santo, Minas Gerais, Maranhão, Rondônia, and Tocantins) had a record number of the BB events since records began in 1998 (INPE, 2018). Our results are consistent with previous

analysis on the 2015 drought effects on the central Amazon during dry season, a region weakly affected by fires in the past. Aragão et al. (2018) found a fire incidence increase by 36% in the Amazon Basin during 2015 in relation to the mean value of the 2003–2015 period. The 2015 drought had the strongest effects in Brazil area north of 20 °S during the dry-to-wet transition season (Fig. 3), where the numbers of the BB outbreaks exceeded 3σ in relation the mean value of the 2003–2016 period in the Brazilian area north of 20° S (Fig. 2). An implication could be that under a dryer and warmer condition in the future, large areas of the Amazon and central Brazil, far from the historical epicenter of deforestation, might be subject to BB outbreaks.

The relationships of the BB outbreaks over tropical Brazil and the variations in the concentration of CO and other gases like the methane (CH_4), carbon dioxide (CO_2), and ozone (O_3) have been discussed in previous studies (Longo et al., 2009; Ribeiro et al., 2018; Aragão et al., 2018). Fig. 4 shows the monthly standardized anomaly time series of the CO averaged over Brazil from July of 2005, 2010 and 2015 to March of the corresponding subsequent year. The time series of the CO anomalies with positive (negative) peaks noted during the dry (dry-to-wet transition) season, of 2005 and 2010 were consistent with the time series of the total number of the BB events (Figs. 1 and 4).

For 2015, the negative CO anomalies occurred during the dry season and the positive ones, from September to March (Fig. 4). In this case, the BB outbreaks in large Brazilian areas (Fig. 2) contributed to the above normal CO concentration from middle September to March. This highlights the impact of the long-lasting 2015 drought on the BB outbreaks and consequently on the CO emissions. Therefore, the forest fires elevated CO concentrations in the Amazon and Cerrado during JASO of 2005 and 2010 and during NDJFM of 2015. The monthly mean values of the number of the BB outbreaks and CO time series over Brazil both show seasonal variations peaking during the dry season, consistent with previous results (Torres et al., 2009; Santos et al., 2017; Ribeiro et al., 2018).

The above analysis on the drought effects on the forest fires indicates that Brazil plays an essential role in the climate change scenario concerning the CO emission into the atmosphere. The results also could suggest a changing scenario for several biomes, in particular for the Amazon and Cerrado. For the dry season, the CO concentration showed positive variations (up to 30%) in central Brazil and southern Amazon during 2005 and 2010 (Fig. 5). The largest positive CO anomalies occurred in the southwestern and southern Amazon (value ~2.8×10^{17} mol cm^{-2}) during the 2005 dry season (Figure not shown). The largest positive variation in the southern Amazon was directly related to a large number of fires in this region during the dry season of 2005 (Figs. 2 and 4). A large number of fires in southern Amazon, part of the Cerrado (Fig. 2), and Bolivia during the 2010 dry period associated with transport process contributed to the largest positive CO anomalies over Central Brazil (value ~2.6×10^{17} mol cm^{-2}) (Figure not shown). In this case, the most considerable positive variation of CO occurred in western and Central Brazil (Fig. 5).

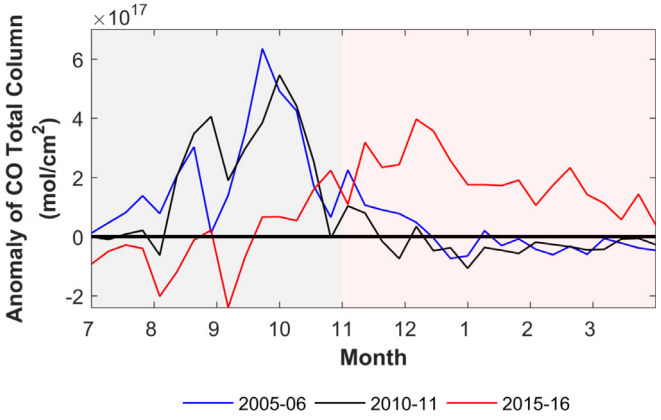

Fig. 4. Eight day CO anomalies averaged over Brazil during the 2005, 2010, and 2015. The grey (red) shade represents the dry (dry-to-wet transition) season. The red shading represents the, dry-to-wet transition season.

The CO concentration showed negative variations (up to −10%) in central Brazil and southern Amazon and the positive variations (up to 10%) in northern Amazon during 2015 (Fig. 5). Contrasting with the 2005 and 2010 dry seasons, when the positive variations of the CO concentration occurred in the southern Amazon, this region experienced negative variations due to the low BB outbreaks during JASO 2015 (Fig. 2). Nevertheless, the positive CO variations were confined in the northern and central Amazon during the 2015 dry season, which were related to forest fires (Fig. 2).

For the dry-to-wet transition season, positive variations (up to 10%) were noted in the eastern Amazon during 2005, negative ones (up to −10%) in the entire Amazon during 2010, and the positive variations (up to 30%) in the central Amazon during 2015 (Fig. 5). The largest positive CO anomalies (3×10^{17} mol cm^{-2}) were confined in the central Amazon, the region with positive BB outbreaks anomalies from November to March of the 2015/16 (Figure not shown).

According to Nobre et al. (2016) and Lovejoy and Nobre (2018), the BB outbreaks in a determinate area and year can lead to drying of surrounding forest and to increasing the vulnerability to fire in the subsequent year, in particular if a severe drought associated with extreme climate events occurs. They also suggested that the negative feedback among BB, deforestation, and climate change may induce to a non-forested ecosystem in the southern, central and eastern parts of the Amazon increasing the biomass exposure and vulnerability in these sectors.

Forest fire incidence in Brazil might be augmented under severe droughts. Severe droughts like those during 2005, 2010, and 2015 caused several direct and indirect environmental and climate impacts. The direct climate impacts include alterations in the chemical properties of the atmosphere (Artaxo et al., 2006; Longo et al., 2009), in the near-surface air temperature, and in rainfall distribution (Sampaio et al., 2007; Artaxo et al., 2013; Marengo and Espinoza, 2016; Panisset et al., 2018). Consequent, indirect impacts are on the radiation and cloud physics (Scott et al., 2018) and the ecosystem carbon stocks (Aragão et al., 2018; Bonini et al., 2018), with important effects on sustainability of the remaining natural vegetation (Van Der Werf et al., 2010).

3. Summary and conclusions

Precipitation deficit in tropical Brazil in the interannual time scale is closely linked to the El Niño and the TNA warming events. The 2005 dryness was associated with the TNA warming, and the 2010 and 2015 dryness with both the El Niño and the TNA warming events. All three droughts affected large areas of the Amazon basin, with those during 2005 and 2010 extending over its western and southwestern parts and the 2015 drought, over the entire Amazon region and continued during the dry-to-wet transition season (Marengo et al., 2008, 2011; Panisset et al., 2018; Aragão et al., 2018). Since the anomalous dryness increases the forest fire incidence (Marengo and Espinoza, 2016; Santos et al., 2017; Aragão et al., 2018), and the variations in the BB outbreaks and CO concentration are closely related, here we re-analyzed the BB and CO variability over Brazil during the 2005, 2010, and 2015 dry years using satellite derived data.

The numbers of the BB outbreaks significantly increased from

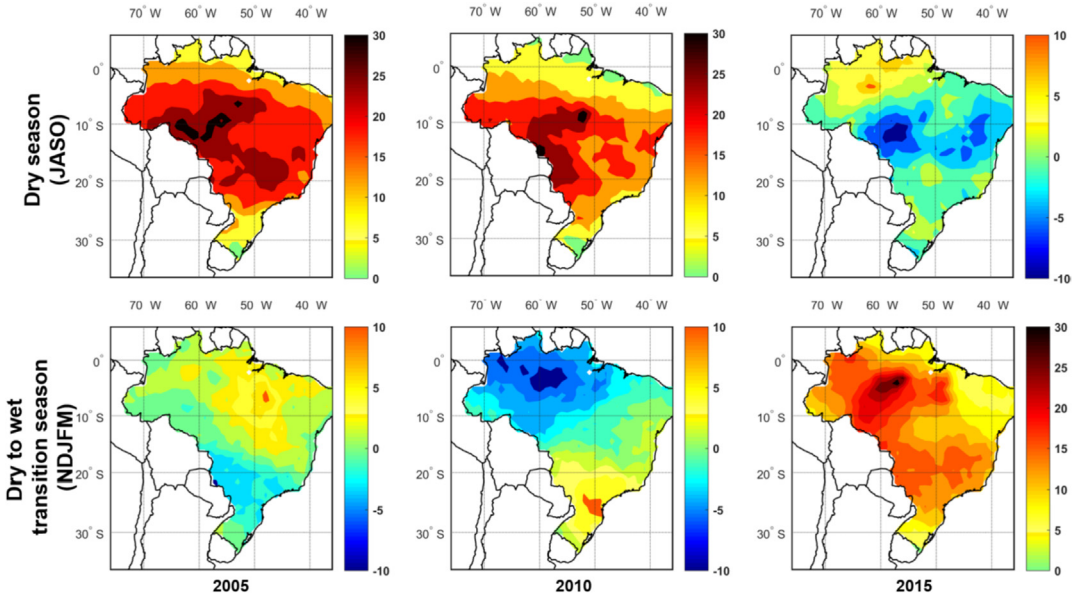

Fig. 5. Seasonal variations (%) of the CO column total in relation to the mean CO column total during the dry and dry to wet transition seasons of 2005, 2010, and 2015.

August to September for the 2005 and 2010 years and surpassed the corresponding ones for the 2015. Nevertheless, the number of the BB events remained high during the dry-to-wet transition season (November to March), with record values from December to March for the 2015–2016 drought. The largest positive BB outbreak anomalies occurred in the southern and southwestern Amazon during 2005 dry season, in central Brazil during 2010 dry season, and in the Brazilian area north of 20°S, an area normally with few fires, during 2015 dry-to-wet transition season. The positive CO variations were directly related to a large number of BB outbreaks in the "deforestation arc" during 2005 dry season, in the southern Amazon, a central part of the Cerrado and Bolivia during the 2010 dry season and in the northern and central Amazon during the 2015 dry-to-wet transition season. The most interesting result is that the persistent dryness in an area, like in the northern and central Amazon during 2015, is a crucial factor in defining the area with high number of BB outbreaks and consequently in increasing the CO concentration in this area. Martin et al. (2017) suggested that the 2015 drought is possibly the first event that shows a major change and that future years in which large areas weakly affected by fires in the past in the Amazon can burn.

Therefore, our results reinforced that the extreme droughts in combination with the indiscriminate fire use might increase the vulnerability of the Brazilian biomes, in particular the southern Amazon and Cerrado. However, the persistent dry condition that spanned from the dry to the dry-to-wet transition season affected areas normally not subject to fires. In a scenario where climate models point to a warmer and dryer future in the Amazon region, intense and persistent dry events might happen. Therefore, this aspect should be taken into consideration for long-term climate and forest fire monitoring tasks, including those aiming to reaching the goals of the Brazilian Government proposed in the Paris Agreement.

Declarations of interest

None.

Acknowledgements

The first author acknowledges the financial support of the Brazilian National Council for Scientific and Technological Development - CNPq (142166/2015-4, 305942/2015-8, 302679/2013-8). The authors thank the Brazilian Federal Agency for Support and Evaluation of Graduate Education (CAPES), Amazonas State Research Foundation (FAPEAM/GOAMAZON and Senior Visiting Professor), for financial support.

The authors thank the two anonymous reviewers for their useful comments and suggestions.

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